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# CARDIAC MEASUREMENT OF HUMAN

# ENERGY EXPENDITURE

A THESIS

Presented to

the Faculty of the Graduate Division

by

Thomas Joel Hall

In Partial Fulfillment

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CARDIAC MEASUREMENT OF HUMAN

ENERGY EXPENDITURE

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## FOREWORD

This investigation was motivated by participation in a major research effort in the area of physiological costs in industrial environments. The research, under the direction of Dr. David C. Ekey, is being conducted at the Georgia Tech School of Industrial Engineering with the purpose of determining an objective physiological measure of human energy expenditure.

Grateful acknowledgement is made of the advice and guidance given the author during the investigation by Dr. Ekey, Dr. Joseph J. Moder and Dr. Joseph E. Moore. Special credit is due to Mr. Thomas L. Newberry of the Georgia Tech Engineering Experiment Station for his assistance in the computer analysis of basic data.

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# SUMMARY

Refinements in time study techniques and other industrial engineering functions are concentrating sharper attention upon rating and allowances. This attention is revealing disturbing situations in many instances; situations due, not only to the relative indefensibility of any allowance but in many more cases, to inherent weaknesses in the particular methods of determining and applying the allowances. Thus, the engineer, realizing that he must justify his time standard, is forced into the position of having to re-examine thoroughly his methods of determining and applying allowances.

The physiological approach in work study has always been attractive for various reasons. This interest is not difficult to understand since, of all the factors making up a time standard, the fatigue allowance is the least defensible and the most open to argument. The objective of this investigation was the determination of an objective physiological measure of human energy expenditure.

Five male college students were randomly selected from a stratified population to perform measured tasks on a friction-brake bicycle ergometer. The subjects were required to perform two replications of two distinct speeds. In each task period the subjects worked five three-minute periods interspersed by six three-minute rest periods. At the end of each three-minute work period recordings were taken of heart rate, galvanic skin response and blood pressure. An analysis of variance was performed on the recorded variables to determine the variant effects

of replication, the different subjects, length of time of task performance, and the two speeds at which the tasks were performed.

Under the conditions of this experiment results showed replication and speed-operator interaction to have no statistically significant effect on the dependent variables. Subject variation was apparent only in blood pressure differential at the five per cent level of significance. Length of time of task performance was highly significant for all dependent variables as was the speed-time interaction. Speed had no significant effect on heart rate or galvanic skin response but was found to cause a highly significant variation in blood pressure differential.

It is apparent the work loads were too severe for precise definition of the task effects on heart rate. However, the results were encouraging in that a significant effect due to length of task was apparent even under these extreme conditions. One of the most encouraging results of this research was the lack of significant variation among subjects for the difference between systolic and diastolic blood pressures.

It is recommended that further research to validate results of this experiment should be conducted over longer periods of time and under load conditions which will permit clarification of the effects of the different contributing factors of fatigue.

# CHAPTER I

## INTRODUCTION

The objective of this investigation was the determination of an objective physiological measure of human energy expenditure. The physiological approach in work study has always been attractive for various reasons. This interest is not difficult to understand since the fatigue allowance and performance rating occupy such a dominant position in the makeup of an industrial time standard. Also, because of all the factors making up a time standard, the fatigue allowance is the least defensible and the most open to argument. This is true regardless of the many recent efforts of experimentation and research on the nature and effects of fatigue.

Engineers cannot adequately evaluate the functional characteristics of a machine on the exclusive basis of utilizing a stop watch and making a time study. It is equally impossible to adequately evaluate the functional capacity of the human machine by the same methods since the stop watch is inherently unable to measure the physiological cost of a job.

Engineers establish their concept of normal performance for a particular operation by estimating the speed at which the effort required to perform the operation appears normal. Some engineers have a standard concept of effort, namely a man walking unburdened on level ground at three miles per hour, which they use as a yardstick. Others carry as a mental concept, a pattern of all the various normal rates they have previously established.

From the pragmatic viewpoint one must agree that these so-called "scientific" methods are operational, but we know they yield only rough approximations to the basic problems of: what constitutes a fair day's work for a given population of workers; what constitutes the optimum pattern of rest periods for a given job; what effect the environmental factors of heat, humidity, and work load have on human energy expenditures; how to rank the physical effort factor among jobs in job evaluation work; and, whether or not the straight-line approximation of increased productivity to bonus incentives accurately relates the additional human energy requirements. Answers to these problems require an accurate method of measuring human energy expenditure and the mechanical work of related activity.

Considerable research effort has been expended over the years in this field, but unfortunately most of this work has been directed toward the refinement of the original concepts of time and motion study. The minuteness of the research leaves unsolved the question of how to attain accurate measurements relative to the human energy factor. Work and rest standards as they now exist are more or less arbitrary. They do not take into account the efficiency and the power of the worker's muscles, heart and lungs; they do not necessarily represent the time needed to perform an operation with a minimum physiological cost and a maximum efficiency of production. They represent even less the time needed to insure an adequate recovery between successive operations. The physiological cost of jobs should be measured and kept within reasonable limits because it is the only accurate means of determining human effort. This effort is an essential factor in job organization, in job evaluation, in the selection of workers and, as a consequence, in labor-management relations.

Numerous experiments have been performed to study the physiological effects of muscular work of varying degrees of intensity (1)(2)(3). It is known that, when shifting from a resting condition to one of physical activity, many physiological functions change from their resting level to a working level (4). Heart rate, blood pressure, cardiac output, pulmonary ventilation, oxygen consumption, chemical composition of the blood and urine, body temperature, and rate of sweating are all modified by muscular activity.

The variable of primary interest in this investigation was the heart rate of a human subject performing measured physical work. Variables of secondary interest were the subject's blood pressure and galvanic skin response. Concomitant variables considered in the experiment were room temperature, relative humidity, time of day, and the subject's height, age, weight, weight-to-height ratio and relative physical fitness. A split-plot experimental design was utilized for the collection of data. Extraction, from the data, of significant sources of variation was accomplished by the analysis of variance technique.

A summary of the literature is appropriate at this point. The order of this summary will in general follow the ordering of the variables listed above.

# CHAPTER II

## REVIEW OF THE LITERATURE

Refinements in time study techniques and other industrial engineering functions are concentrating sharper attention upon rating and allowances. This attention is revealing disturbing situations in many instances; situations due, not only to the relative indefensibility of any allowance but in many more cases, to inherent weaknesses in the particular methods of determining and applying the allowances. Thus, the engineer, realizing that he must justify his time standard, is forced into the position of having to re-examine thoroughly his methods of determining and applying the allowance.

Is the amount of allowance that permits the worker to maintain the optimum productivity rate sufficient to prevent undue fatigue? Consider carefully the last sentence of the following quotation from Viteles (5):

> For every type of work there exists an optimal speed, which will make it possible to get as much as possible done with the least expenditure of energy and without increasing the feelings of fatigue, discomfort and ill health. The determination of these speeds, from the viewpoint of human efficiency, is almost an untouched field. They have been fixed again and again, for many types of work, with respect to the highest rate or amount of production, but there is reason for believing that this rate often conflicts with the optimum welfare of the worker.

One very important group of methods of determining allowances consists of those that obtain their information from laboratory research tests. This information must of course be translated to, and proven in, industrial situations.

Allowances determined by methods in this group have important advantages and disadvantages. It is possible in a laboratory test to obtain a degree of isolation of a factor of fatigue to be measured that would be impractical or impossible under other circumstances. Hence, results are obtainable which give valuable and useful information on the investigated factor of fatigue.

This same isolation process, however, frequently makes it impossible to apply accurately those results directly to a practical industrial problem. Very often the adaptation process requires assumptions and estimates that destroy the original accuracy of the data.

One of the earliest approaches to physiological measurements is known as the $CO_2$ method. Pioneers in the field attempted to obtain reliable knowledge about human energy expenditure by measuring the amount of oxygen converted into carbon dioxide (6). The method provided extremely valuable information on the energy efficiency of certain prototype jobs.

The complexity of this early equipment has led some investigators to a negative opinion of physiological measurements. Ingenohl (7) states that "physiological measurements can hardly be justified for a mere quick check to determine which one of several jobs actually requires the greater physical exertion." Recent advances (8) tend to nullify this view however, and lend credence to the oxygen-consumption method of physiological measurement.

Perhaps the most operational of the physiological measurement schemes to date is that of Brouha (9). The principle of the method used in Brouha's research was developed in the Harvard Fatigue Laboratory. It consists of counting the pulse rate for 30 seconds at three one-minute intervals during the first three minutes of the recovery period after the termination of work and while the subject is sitting quietly. From these pulse rates a "heart rate recovery curve" can be drawn which indicates the actual values of the pulse and the rate of recovery toward resting level. The heavier the physiological load the higher the heart rate and the more slowly it returns to its resting level. Thus the physiological stress for a specific job can be determined from the recovery pulse rate measurements. Brouha points out that:

> The onset of fatigue can be predicted from heart rate recovery curves. When no satisfactory recovery can take place between a series of successive operations the first pulse rate after work becomes progressively higher and the heart rate remains at a high level for a progressively longer time during the recovery period. The return toward the resting level is very slow and definitely points to the existence of physiological fatigue in these workers.

Work by Young (10) on an experimental basis appears to support that of Brouha. Young investigated the possibility of using the heart rate as an objective method of rating operator performance on jobs of varying physical intensity. It was concluded that prediction, from heart rate, of task pace energy requirements was possible within the limitations of the experiment. The work of both Young and Brouha appears to lack operational qualities in that the work increment of heart rate is not utilized.

Some investigators contend that fatigue, due to its subjective and complex qualities, cannot be compensated for by purely physiological evaluation. From the few studies attempting to isolate these subjective elements it appears that the difficulty lies in their proper definition (11). Comparisons of findings by Kerr (12) and Brouha indicate that the onset of subjective and physiological fatigue for large groups in the work situation is closely related.

To date no satisfactory relationship has been established between blood pressure and physiological performance capacity. Wide ranges of pressures have been recorded with subjects adjudged to be of the same physical fitness (13). This may be due in part to the inaccuracy of blood pressure determinations and in part to the medical classification of physical fitness. It is clearly recognized that arterial pressures cannot be measured with precision by sphygmomanometers (14). Direct registration of pressures by calibrated intra-arterial manometers has shown that even during quiet breathing, systolic and diastolic pressures vary from beat to beat by several mm Hg, and that these differences are greatly intensified during states of deep breathing. The errors of typical clinical measurement of blood pressure can be summarized by saying that in normal persons a mean error of plus or minus 8 mm Hg may be expected in individual readings of systolic and diastolic pressures (15).

Another line of physiological tests uses the electrical resistance of the skin (16). This resistance as measured by ordinary physical methods, shows variation with the activity of the subject. There is now evidence that as the subject becomes more active muscularly, as he becomes involved in an emotion, or as he engages in mental work, the electrical skin resistance is reduced. Consequently, skin resistance is possibly an index of effort and fatigue. It has long been known that the electrical resistance of the skin falls after sudden stimuli. These fluctuations are now generally regarded as a function of sweat gland activity which is controlled by the sympathetic nervous system, a portion of the nervous system which has to do with the control of circulation.

The level of skin resistance is now often regarded as dependent upon the general level of excitation of the muscles of the body. It is therefore hoped that it will provide an index of the total muscular activity of the body. There is still much fundamental research to be done in determining exactly what it measures, how much influence relatively unimportant factors may have upon the level of resistance, and how accurate it is as a measure of the amount of effort being expended as well as a reflection of the relative changes of effort.

It is known that the human body performs best when it can maintain its temperature at about 98.6°F. Muscular work produces heat and the more work done the more heat which has to be dissipated to maintain normal body temperature.

As the temperature of the work environment approaches, or exceeds, that of the body, the main method by which the body can dissipate heat is by evaporative cooling; i.e., sweating. During sweating, the amount of blood reaching the surface of the body is greatly increased to facilitate loss of heat. As a consequence, for the same amount of work the heart rate becomes progressively faster as the body temperature increases (17)(18). In a study conducted by the DuPont Company (19):

> ...the reactions of a group of several hundred workers were followed at intervals from March to July. During that period the temperature in the plant shifted from an average of 78°F to 100°F. The average pulse rate after work increased from 92 beats per minute in March to 116 beats per minute in July.

The amount of heat that can be dissipated by evaporation depends not only on the air temperature but also upon the air movement and the humidity. It is generally agreed that below 80$^{\circ}$F the humidity of the air has little effect in producing physiological stress; but, as air temperature increases above 80$^{\circ}$F, humidity becomes an important factor (20). When evaporative cooling decreases, thus reducing the efficiency of the body for dissipating heat, strenuous work cannot be maintained for long periods of time. Fatigue and exhaustion are reached rapidly with high heart rates, high body temperatures, and very slow recovery processes after work.

In laboratory studies of human energy expenditure the time of day at which task performance occurs has been found highly significant with respect to heart rate following work (21). This agrees closely with studies of subjective fatigue in actual work situations (22). If, in physiological studies, the time of day of task performance cannot be strictly controlled it is perhaps best, as was done in this investigation, to thoroughly randomize the performance times so that the error introduced by this variable will be evenly distributed.

The age of subjects appears to have no significant bearing on physiological studies if the range of ages of subjects is confined to limits of 17 to 30 (23). Above this range a pace set for younger men is maintained by older men only with an effort which would seem likely in course of time to cause strain.

Brouha (24) points out that it is possible for some individuals to perform hard muscular work with less acceleration in heart rate than is attained by others who fulfill a more minimal task and that it is possible for one man to finish a five minute run with a heart rate no greater than that shown by another who walks for the same length of time. This finding vividly illustrates the marked variations in efficiency in muscular work to be observed among "normal" young men. Brouha's experiments show that while a complete and careful medical examination distinguishes the "healthy" from the "ill", physiological measurements are indispensable for the further and more accurate distribution of normal individuals according to a scale of physiological values based on characteristic functional capacities. These experiments indicate also that physiological differences which already exist during rest among normal individuals are enhanced when the organism is put to work and approaches its maximum capacity.

There is no doubt that higher standards of living, social security, shorter working hours, greater safety, better hygiene and medical care have improved the life of the modern worker. Never the less (25):

> Management, unaware of the importance of human physiology and interested only in the fact that a worker is good, mediocre or bad as far as productivity is concerned, does not realize that it would lead to major industrial and social progress to know the physiological reactions of the individual on the job.

# CHAPTER III

## INSTRUMENTATION AND EQUIPMENT

The major pieces of equipment used for data collection in this research were:

1. A Sanborn series 150 M medical recording system.
2. A Waters C-225 cardiotachometer.
3. A Waters HS-10 heart sound amplifier.

Instrumentation for manual data collection included:

1. A galvanic skin response meter.
2. An aneroid sphygmomanometer and a Ford-Bowles stethoscope for blood pressure recordings.
3. A direct reading electric hygrometer for relative humidity recordings.
4. A decimal-minute stop watch for timing task and rest periods.

Expenditure of the subjects' energy was provided for by use of a friction-brake bicycle ergometer. A functional description of this device and the major pieces of recording equipment is presented in the material below.

Recording System.--Outputs from the cardiotachometer and the heart sound amplifier were recorded with a Sanborn series 150 M medical recording system (Figure 1-A). This system is composed of a four-channel recording unit, four individual driver amplifiers and two electrocardiograph pre-amplifiers.

The recording unit consists of a bank of D'Arsonval galvanometers used to record a number of variables simultaneously. Each galvanometer movement drives a writing arm which deflects a hot-wire ribbon stylus across the heat-sensitive paper tape while the paper is moving across a knife-edge writing platen. The final recording is permanent, instantaneous and in true rectangular coordinates. Controls on the face of the recording unit permit a wide range of tape speeds and an automatic timing signal.

The ECG preamplifier is used for recording electrocardiograms and other physiological phenomena. In this research it was used to amplify the heart rate signal to the recorder. Facility features of the preamplifier are: input sockets for connecting external equipment; a sensitivity control for adjusting pulse deflections; a centering control for adjusting the trace base line; and an attenuator for introducing attenuation ratios of 50, 20, 10, 5, 2 or one into the input signal.

Controls on the face of the driver amplifier units adjust the power input to the preamplifiers and the stylus temperatures of the recording galvanometers.

Cardiotachometer.--The Waters C-225 cardiotachometer (Figure 1-B) is designed to measure and indicate heart rate of animals and humans. The cardiotachometer is activated by the cardiac potential. Heart rates measured from 40 to 360 beats per minute are indicated on a meter. The meter is divided into two scales to provide easy reading. Each heart beat is also indicated by the flash of a neon light. Outputs are provided to record both the instantaneous heart rate and the electrocardiogram.

The instrument consists of an amplifier with a 60-cycle rejection

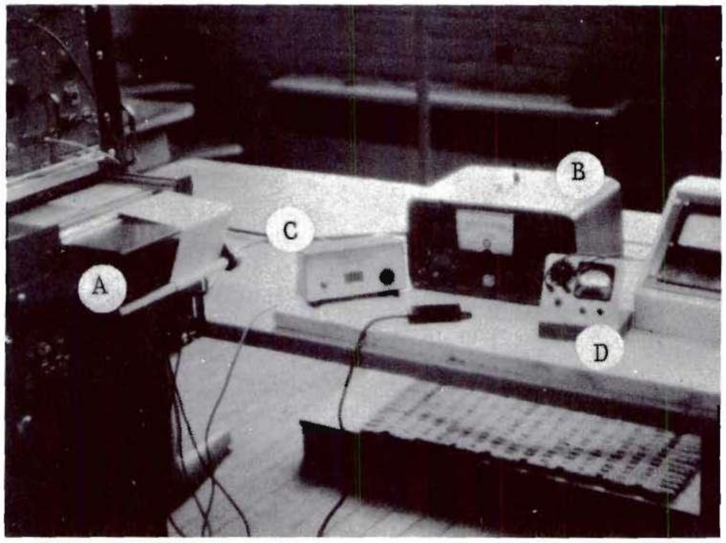


Figure 1. Recording Equipment: (A) Medical Recording System, (B) Cardiotachometer, (C) Heart Sound Amplifier, (D) Galvanic Skin Response Meter.

filter, a timing circuit, a meter and a calibrating device. Input to the amplifier is attained through three electrodes attached to the subject, two on the chest and a neutral electrode on the left leg.

The four and one-half inch meter has two linear scales, one calibrated from 40 to 120 beats per minute and the other calibrated from 120 to 360 beats per minute. Every artifact can be indicated with an instantaneous signal or an external damping circuit provides for moderate or heavy damping of the signal.

The timing circuit measures the interval between beats and holds this value on the meter until the next beat. This unique method minimizes error due to artifacts, a common problem with integrating and averaging circuits. A synchronous motor provides calibrating pulses of

40, 120, and 360 beats per minute.

Heart Sound Amplifier.--The Waters HS-10 heart sound amplifier (Figure 1-C) is designed to amplify heart sound signals from a Waters HSM-1 heart sound microphone. The instrument consists of a three stage transistor amplifier, a high frequency filter, a half wave rectifier, a full wave rectifier and an integrating or summing circuit. In this research the sound amplifier was used only as a monitor on the performance of the cardiotachometer.

Galvanic Skin Response Meter.--This apparatus (Figure 1-D), used to record skin conductance, is essentially a microammeter calibrated to read directly in units of conductance. By means of electrodes placed in the palms of the subject's hands the meter reads the current passing through the body between the two hands. The circuit (26) is designed so that the measured current is exactly equal to conductance.

Friction-Brake Bicycle Ergometer.--The task device used in this research (Figure 2) was a bicycle ergometer (27) provided with a calibrated spring brake for varying the work load. An added feature of this ergometer was an electrically driven tachometer by which the subject could regulate his speed. Structural features of the device include adjustments for seat height, length of reach to the hand grips, and radius of pedal arc.

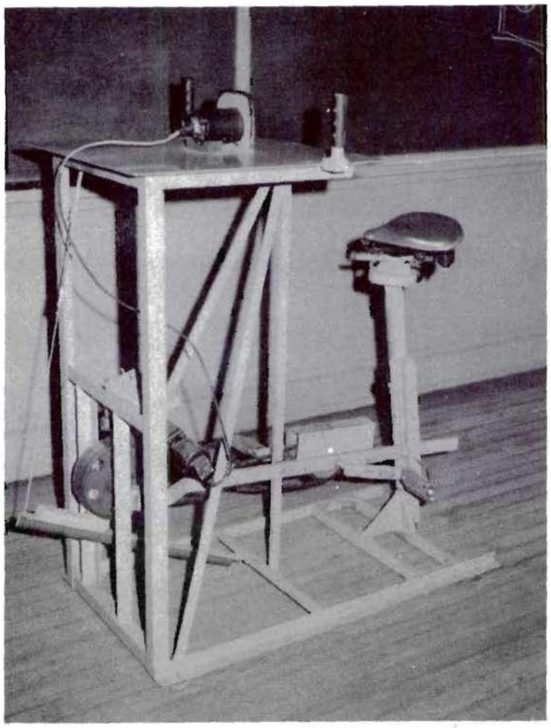

Figure 2. Friction-Brake Bicycle Ergometer.

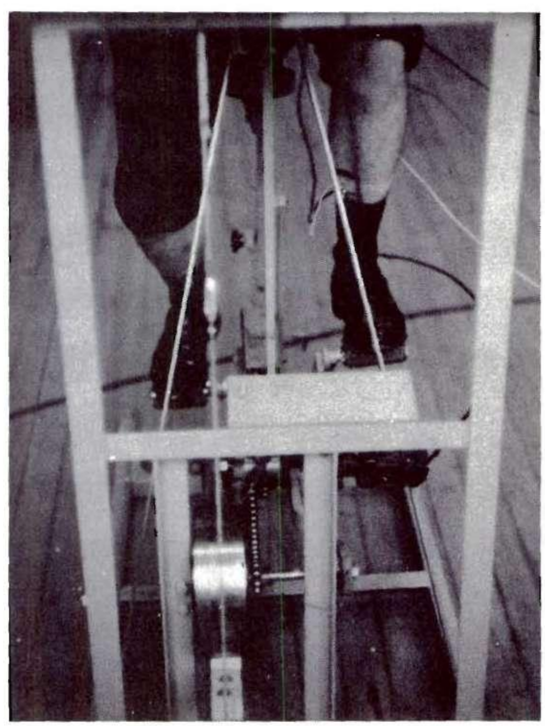

Figure 3. Forward View of the Ergometer.

# CHAPTER IV

## EXPERIMENTAL PROCEDURE

In an attempt to determine if some variable, characterized by the performance of the heart, could be significantly associated with energy expended by a human subject it was first necessary to find subjects willing to cooperate in supplying the data. It was also necessary to design a standard task, to select and quantify variables pertinent to the research, and to devise an experimental design which would facilitate collection and analysis of useful data.

Subject Selection.--Five male college students were selected at random from a stratified population (a fraternity group of sixty students) to perform standard tasks on the bicycle ergometer. These subjects were selected on a basis of willingness of the entire fraternity group to participate. No individual motivation was introduced by the author. As a further qualification the subjects had all previously passed the Georgia Tech physical fitness tests and had participated in the physical education program required of all students at Georgia Tech.

Tasks.--Two standard tasks were selected for the subjects. The order of task performance for each subject was randomized for each replication of the experiment. Each task utilized a constant brake load and the subject was required to maintain by visual observation a tachometer reading of either 18 revolutions per minute (slow speed) or a reading of 36 revolutions per minute (high speed). Effective energy outputs at these speeds were calculated to be 2119 foot-pounds per minute (0.064 horsepower) and 4238 foot-pounds per minute (0.128 horsepower) respectively. At each speed the subject was required to perform five three-minute cycles of work interspersed by six three-minute rest periods for a total elapsed time of 33 minutes. A continuous trace of the subject's heart rate was recorded throughout the entire 33 minutes. Blood pressure and galvanic skin response were recorded three minutes prior to the first work cycle and immediately following all work cycles. This recording procedure (Figure 4) yielded a reference reading and five progressive work readings for each dependent variable. After the subject had completed the two tasks, the experiment was replicated with the order of task performance again randomized. Task performances were scheduled with the restriction that no subject would perform more than one task within the same 24-hour period. Figure 5 illustrates the relation between the four main effects of speed, time, replication and subjects.

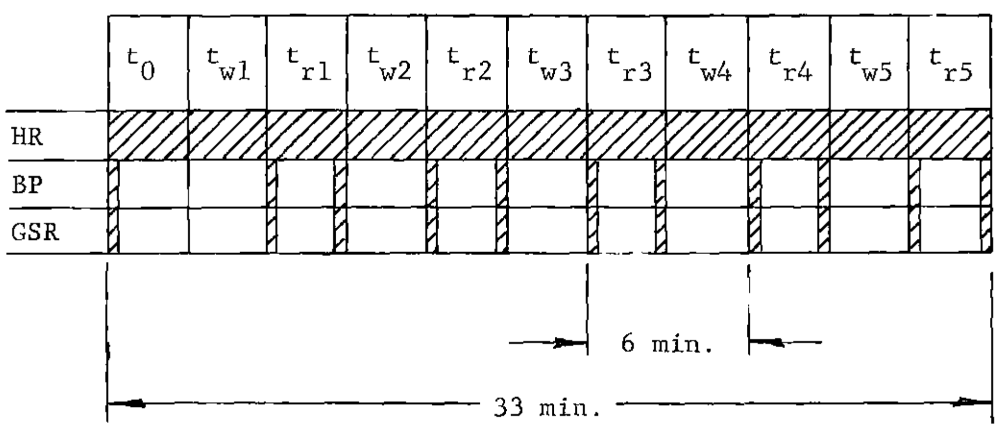


Figure 4. Recording Schedule; Recording Periods for the Indicated Dependent Variables Are Defined by the Crosshatched Areas.

| | Replication 1 | | | | | | | | | | | | Replication 2 | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Speed 1 | | | | | | Speed 2 | | | | | | Speed 1 | | | | | | Speed 2 | | | | | |
| | $t_0$ | $t_1$ | $t_2$ | $t_3$ | $t_4$ | $t_5$ | $t_0$ | $t_1$ | $t_2$ | $t_3$ | $t_4$ | $t_5$ | $t_0$ | $t_1$ | $t_2$ | $t_3$ | $t_4$ | $t_5$ | $t_0$ | $t_1$ | $t_2$ | $t_3$ | $t_4$ | $t_5$ |
| $O_1$ | | | | | | | | | | | | | | | | | | | | | | | | |
| $O_2$ | | | | | | | | | | | | | | | | | | | | | | | | |
| $O_3$ | | | | | | | | | | | | | | | | | | | | | | | | |
| $O_4$ | | | | | | | | | | | | | | | | | | | | | | | | |
| $O_5$ | | | | | | | | | | | | | | | | | | | | | | | | |

Figure 5. Experimental Design.

<u>Concomitant Variables</u>.--Although the concomitant variables were, as a rule, beyond control they were observed and recorded for possible future analysis. The environmental concomitants recorded were room temperature, relative humidity and time of day of task performance. Subject concomitants recorded were age, height, weight, weight to height ratio and relative physical fitness. The experiments were conducted during the month of May, 1960, with unseasonally high temperatures occurring during the afternoon recording periods. Dry-bulb room temperature was recorded at the beginning and end of each task performance and ranged from a high of 93.0 to a low of 74.0 degrees Fahrenheit. Relative humidity, recorded concurrently with temperature, ranged from 70.0 to 42.0 per cent. Task periods were scheduled between eight A.M. and six P.M. An attempt was made to randomize time of day of task performance but this was of course influenced by the subjects' class schedules. The subjects' ages ranged from 17 to 20 years.

Height of subjects ranged from 71 to 76 inches while weight of subjects ranged from 145 to 180 pounds resulting in a range of weight-to-height ratios from 2.02 to 2.47 pounds per inch. A two-level stratification of physical fitness appeared to exist among the subjects. These levels were subjectively classified as "0" for "average" fitness and "1" for "above average" fitness. A summary of the subject concomitants appears in Table 1.

Table 1. Subject Concomitant Data.

| Subject | Age | Height | Weight | Wgt/Hgt | Fitness |
|---|---|---|---|---|---|
| $O_1$ | 20 | 71" | 145 # | 2.02 #/in. | 0 |
| $O_2$ | 18 | 73" | 180 # | 2.47 #/in. | 1 |
| $O_3$ | 17 | 74" | 155 # | 2.09 #/in. | 1 |
| $O_4$ | 19 | 72" | 175 # | 2.43 #/in. | 1 |
| $O_5$ | 20 | 76" | 170 # | 2.24 #/in. | 0 |

Laboratory Environment.--The experimentation was conducted in a second floor room of the Georgia Tech School of Industrial Engineering building, formerly a classroom, approximately 20 feet wide by 30 feet in length. The ceiling and upper portion of the walls were painted pale green with the lower four feet of the walls being a somewhat darker shade of green. Ventilation was provided for by a door transom, four window transoms, and two double casement windows which were kept open at all times. The one double door was kept closed while a task performance was in progress although subjects not under observation were permitted to enter or leave at their convenience. The noise level was approximately that of a normal class room since classes were being conducted in the remainder of the building. Lighting was provided for by fluorescent fixtures and by indirect sunlight.

Procedure.--An explanation of the procedure employed during any one task performance will suffice since all such performances were conducted in an identical manner.

Prior to the experimentation all subjects were called into the laboratory for orientation. They were instructed on the general nature of the experiment but not on the specific measurements, objectives or hypothesized results. Each subject was given a prearranged schedule of his performance times and instructed to bring gym shorts and hard soled shoes to the laboratory.

According to the preassigned times the subject arrived at the laboratory at the beginning of the hour. Other subjects were permitted to attend and observe in a non-participating capacity if they so desired. After changing clothes the subject was told to rest in a chair for a minimum of ten minutes and was questioned as to his activities of the past 24 hours. He then mounted the bicycle ergometer while the observer and an assistant taped the recording apparatus to his body in the manner described below. A blood pressure cuff was taped to the subject's upper left arm so that it was in position for use throughout the task period. Copper electrodes from the GSR meter were coated with a standard electrode paste and taped to the subject's palms. Two silver electrodes were coated with paste and mounted under a rubber chest band placed around the subject's chest so that one electrode was positioned over the apex of the heart and the other under the right arm. A third silver electrode, neutral, was taped to the subject's lower left leg. These three electrodes were then connected to the cardiotachometer and a few centimeters of recording tape were run off to check the clarity of the cardiac signal.

When the recording equipment was functioning satisfactorily, the subject was told which speed he was expected to maintain on the ergometer. Room temperature, relative humidity and blood pressure readings were taken and the observers positioned themselves at the controls of the recording equipment (Figure 6). The cardiotachometer

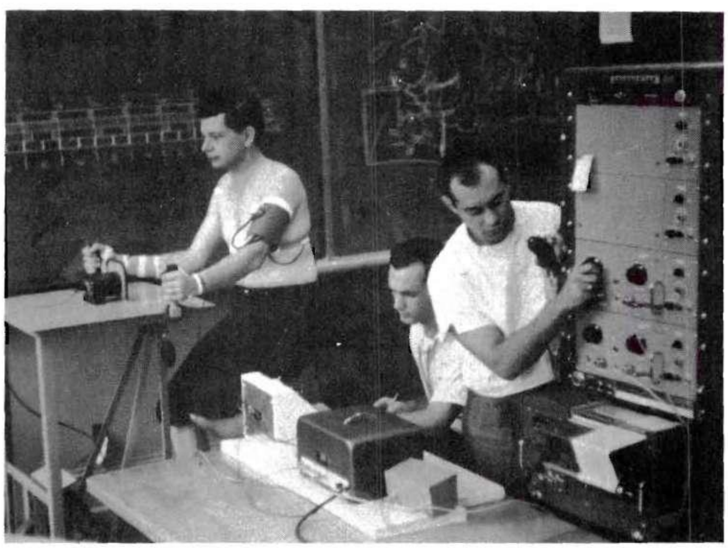

Figure 6. Recording Heart Rate and Galvanic Skin Response During a Task Performance.

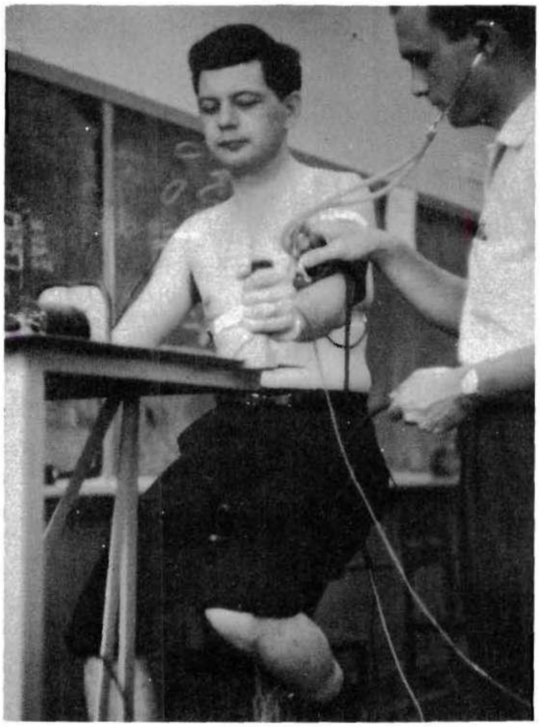

Figure 7. Recording Blood Pressure at the End of a Work Period.

and the four-channel recorder were calibrated as a unit so that reference points of 40, 120, and 240 beats per minute were precisely located on the recording tape. After calibration the recorder was allowed to run at a continuous tape speed of one millimeter per second throughout the remainder of the experiment. The subject was instructed to remain quietly in position for three minutes. When this three-minute rest period had elapsed the subject was told to begin work. At the end of the three-minute work period the subject was told to stop and simultaneous readings of galvanic skin response and blood pressure were recorded. It was necessary for one of the observers to move to the ergometer for manual recording of the blood pressure readings (Figure 7). The subject then rested for a third three-minute period at the end of which readings were again taken. These rest period readings were retained but not utilized in the final analysis of the experiment. The above procedure was repeated until the subject had completed the entire cycle of rest and work periods (Figure 4).

At the conclusion of the task performance readings were again taken of room temperature and relative humidity. The recording apparatus was removed from the subject and he was permitted to leave after being reminded of his next scheduled task time. When a subject had completed all four tasks he was given access to the results of his individual recordings.

# CHAPTER V

## ANALYSIS AND RESULTS

A split-plot factorial design was used for evaluation of the effects of speed, work time, and replication on the dependent variables among the five subjects. As illustrated in Figure 5 the main plot variables consist of speed, replication and subjects. The split-plot effect is introduced by the time divisions. This split-plot division adds to the evaluation of the time effect a degree of precision which could not be obtained with a completely crossed time design.

During the experimentation subjects "$O_1$" and "$O_5$" became exhausted and were unable to complete the second replication at "Speed 2" due to excessive heat. Synthesis of the missing data would have reduced the degrees of freedom to a point which would have been excessively restrictive on the analysis of variance. Consequently the original experimental design was broken down into two separate designs, neither of which utilized the portion of the second replication containing the missing data points. The first of these designs (Figure 8-a) consisted of first replication data for all subjects. This design was designated as "Experimental Design 265" for the two speeds, six time periods and five subjects. The second design (Figure 8-b) consisted of data from both replications for subjects "$O_2$", "$O_3$", and "$O_4$". This design was designated as "Experimental Design 2623" for the two speeds, six time periods, two replications and three subjects.

| | Speed 1 | | | | | | Speed 2 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $t_0$ | $t_1$ | $t_2$ | $t_3$ | $t_4$ | $t_5$ | $t_0$ | $t_1$ | $t_2$ | $t_3$ | $t_4$ | $t_5$ |
| $O_1$ | | | | | | | | | | | | |
| $O_2$ | | | | | | | | | | | | |
| $O_3$ | | | | | | | | | | | | |
| $O_4$ | | | | | | | | | | | | |
| $O_5$ | | | | | | | | | | | | |

Figure 8-a. Experimental Design 265.

| | Replication 1 | | | | | | | | | | | | Replication 2 | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Speed 1 | | | | | | Speed 2 | | | | | | Speed 1 | | | | | | Speed 2 | | | | | |
| | $t_0$ | $t_1$ | $t_2$ | $t_3$ | $t_4$ | $t_5$ | $t_0$ | $t_1$ | $t_2$ | $t_3$ | $t_4$ | $t_5$ | $t_0$ | $t_1$ | $t_2$ | $t_3$ | $t_4$ | $t_5$ | $t_0$ | $t_1$ | $t_2$ | $t_3$ | $t_4$ | $t_5$ |
| $O_2$ | | | | | | | | | | | | | | | | | | | | | | | | |
| $O_3$ | | | | | | | | | | | | | | | | | | | | | | | | |
| $O_4$ | | | | | | | | | | | | | | | | | | | | | | | | |

Figure 8-b. Experimental Design 2623.

Heart rate data was obtained directly from the recording tapes (Figure 9) by counting the number of millimeters the trace was deflected above the base line at the cessation of work. To obtain heart rate in beats per minute these numbers were multiplied by the appropriate scale factor, depending upon whether the cessation of work occurred when the cardiotachometer was on low scale or on high scale. For purposes of computer analysis heart rate was designated as variable "$y_1$" and coded by reducing the actual values by 75. Galvanic skin response, designated as variable "$y_3$", was recorded manually from direct GSR meter readings taken at the end of each three-minute work cycle. These values, recorded in mhos, were multiplied by ten and reduced by 59 to form the GSR coded data. Blood pressure observations were recorded in millimeters of mercury by the standard method of systolic over diastolic pressure. These pressure readings were analyzed

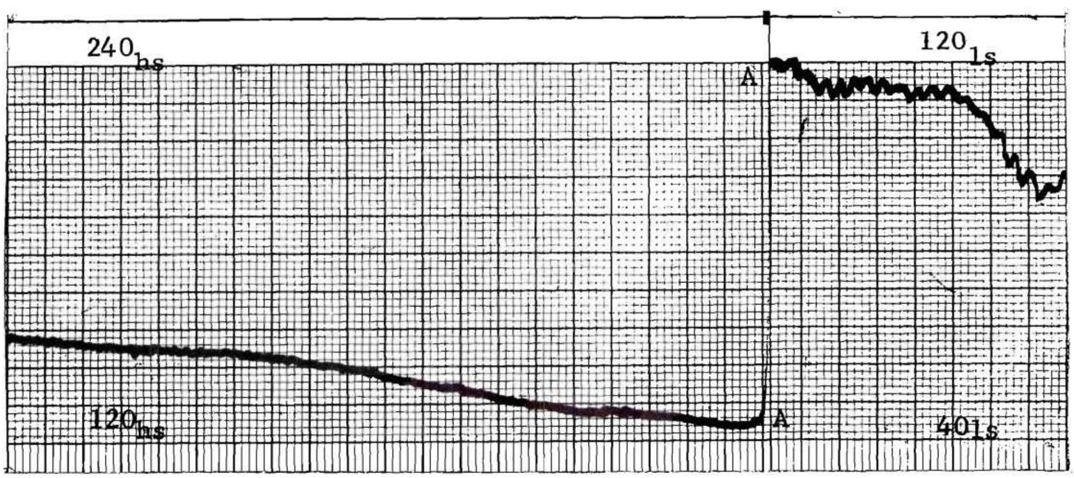


Figure 9. Heart Rate Trace Recorded During Work.

in three separate configurations: the difference, "$y_5$", between systolic and diastolic pressure was coded by reducing the actual differences by 22 while the absolute systolic pressure, "$y_6$", was reduced by 66 and the absolute diastolic pressure, "$y_7$", was reduced by 30.

Tables 2 and 3 list the sources of variation for experimental designs 265 and 2623 together with their respective sums of squares. Tables 4 and 5 list for each dependent variable the calculated F ratio, and the five per cent and one per cent F distribution values for the associated degrees of freedom. Results of the analysis of variance are discussed below for each source of variation.

Replication.--Under the conditions of this experiment replication did not significantly affect any of the dependent variables. This indicates that the error among trials was apparently well controlled with no significant variation due to learning or conditioning.

Subjects.--It was expected, as pointed out in the introduction, that blood pressure would be significantly different among subjects. Tables 4 and 5 show however that the only marked variation in blood pressures occurred at the five per cent level of significance in experimental design 265. This supports the subjective stratification of the subjects according to fitness. Heart rate showed no significant variation among subjects, and GSR was only slightly affected at the five per cent level in experiment 2623.

Speed.--It was expected that speed would be one of the most significant sources of variation for all dependent variables since the mechanical work accomplished at the fast speed was nearly double that accomplished

Table 2. Split-Plot Sources of Variation; Experimental Design 265.

| Source | D.F. | Sums of Squares |
|---|---|---|
| L | 1 | $\sum_{i} T^2_{i..}/30 - T^2_{...}/60$ |
| O | 4 | $\sum_{k} T^2_{..k}/12 - T^2_{...}/60$ |
| LO* | 4 | $\sum_{ik} T^2_{i.k}/6 - \sum_{i} T^2_{i..}/30 - \sum_{k} T^2_{..k}/12 + T^2_{...}/60$ |
| T | 5 | $\sum_{j} T^2_{.j.}/10 - T^2_{...}/60$ |
| LT | 5 | $\sum_{ij} T^2_{ij.}/5 - \sum_{i} T^2_{i..}/30 - \sum_{j} T^2_{.j.}/10 + T^2_{...}/60$ |
| OT | 20 | $\sum_{jk} T^2_{.jk}/2 - \sum_{j} T^2_{.j.}/10 - \sum_{k} T^2_{..k}/12 + T^2_{...}/60$ |
| OTL** | 20 | $\sum_{ijk} T^2_{ijk} - \sum_{ij} T^2_{ij.}/5 - \sum_{ik} T^2_{i.k}/6 - \sum_{jk} T^2_{.jk}/2 + \sum_{i} T^2_{i..}/30 +$ $+ \sum_{j} T^2_{.j.}/10 + \sum_{k} T^2_{..k}/12 - T^2_{...}/60$ |
| Total | 59 | $\sum_{ijk} y^2_{ijk} - T^2_{...}/60$ |

* main plot residual

** split-plot residual

Table 3. Split-Plot Sources of Variation; Experimental Design 2623.

| Source | D.F. | Sums of Squares |
|---|---|---|
| R | 1 | $\sum_{k} T^2_{..k.}/36 - T^2_{....}/72$ |
| L | 1 | $\sum_{i} T^2_{i...}/36 - T^2_{....}/72$ |
| O | 2 | $\sum_{l} T^2_{...l}/24 - T^2_{....}/72$ |
| LO | 2 | $\sum_{il} T^2_{i..l}/12 - \sum_{i} T^2_{i...}/36 - \sum_{l} T^2_{...l}/24 + T^2_{....}/72$ |
| (RL + RO + LRO)* | 5 | $\sum_{ikl} T^2_{i.kl}/6 - \sum_{il} T^2_{i..l}/12 - \sum_{k} T^2_{..k.}/36 + T^2_{....}/72$ |
| T | 5 | $\sum_{j} T^2_{.j..}/12 - T^2_{....}/72$ |
| LT | 5 | $\sum_{ij} T^2_{ij..}/6 - \sum_{j} T^2_{.j..}/12 - \sum_{i} T^2_{i...}/36 + T^2_{....}/72$ |
| OT | 10 | $\sum_{jl} T^2_{.j.l}/4 - \sum_{j} T^2_{.j..}/12 - \sum_{l} T^2_{...l}/24 + T^2_{....}/72$ |
| (RT + RLT + ROT + ROTL + OTL)** | 40 | $\sum_{ijkl} y^2_{ijkl} - \sum_{ikl} T^2_{i.kl}/6 - \sum_{ij} T^2_{ij..}/6 - \sum_{jl} T^2_{.j.l}/4 + \sum_{i} T^2_{i...}/36 +$ |
| | | $+ \sum_{j} T^2_{.j..}/12 + \sum_{l} T^2_{...l}/24 - T^2_{....}/72$ |
| Total | 71 | $\sum_{ijkl} y^2_{ijkl} - T^2_{....}/72$ |

*main plot residual

**split-plot residual

Table 4. Analysis of Variance Data;
Experimental Design 265.

| Dependent Variable | Source | D.F. | Estimated F Value | 5% F Value | 1% F Value |
|---|---|---|---|---|---|
| HR | L | 1/4 | 6.9589 | 7.71 | 21.2 |
| HR | O | 4/4 | 0.9342 | 6.39 | 16.0 |
| HR | T** | 5/20 | 80.8194 | 2.71 | 4.10 |
| HR | LT** | 5/20 | 17.0512 | 2.71 | 4.10 |
| HR | OT | 20/20 | 1.8889 | 2.12 | 2.94 |
| GSR | L | 1/4 | 1.5866 | 7.71 | 21.2 |
| GSR | O | 4/4 | 2.0450 | 6.39 | 16.0 |
| GSR | T** | 5/20 | 28.4068 | 2.71 | 4.10 |
| GSR | LT | 5/20 | 1.7569 | 2.71 | 4.10 |
| GSR | OT | 20/20 | 0.8843 | 2.12 | 2.94 |
| S - D | L** | 1/4 | 106.2757 | 7.71 | 21.2 |
| S - D | O* | 4/4 | 10.3241 | 6.39 | 16.0 |
| S - D | T** | 5/20 | 32.0810 | 2.71 | 4.10 |
| S - D | LT** | 5/20 | 9.1063 | 2.71 | 4.10 |
| S - D | OT | 20/20 | 1.0155 | 2.12 | 2.94 |
| S | L** | 1/4 | 46.2021 | 7.71 | 21.2 |
| S | O* | 4/4 | 8.1902 | 6.39 | 16.0 |
| S | T** | 5/20 | 16.0850 | 2.71 | 4.10 |
| S | LT** | 5/20 | 7.0213 | 2.71 | 4.10 |
| S | OT | 20/20 | 1.0892 | 2.12 | 2.94 |
| D | L* | 1/4 | 16.6302 | 7.71 | 21.2 |
| D | O | 4/4 | 0.7878 | 6.39 | 16.0 |
| D | T** | 5/20 | 29.6392 | 2.71 | 4.10 |
| D | LT | 5/20 | 2.4945 | 2.71 | 4.10 |
| D | OT | 20/20 | 0.5904 | 2.12 | 2.94 |

* significant at the 5% level
** significant at the 1% level

Table 5. Analysis of Variance Data;
Experimental Design 2623.

| Dependent Variable | Source | D.F. | Estimated F Value | 5% F Value | 1% F Value |
|---|---|---|---|---|---|
| HR | R | 1/5 | 0.0070 | 6.61 | 16.3 |
| HR | L | 1/2 | 11.3069 | 18.5 | 98.5 |
| HR | O | 2/5 | 1.5043 | 5.79 | 13.3 |
| HR | LO | 2/5 | 1.7038 | 5.79 | 13.3 |
| HR | T** | 5/10 | 106.2483 | 3.33 | 5.64 |
| HR | LT** | 5/40 | 26.1281 | 2.45 | 3.51 |
| HR | OT** | 10/40 | 3.5137 | 2.08 | 2.80 |
| GSR | R | 1/5 | 0.6908 | 6.61 | 16.3 |
| GSR | L | 1/2 | 2.8199 | 18.5 | 98.5 |
| GSR | O* | 2/5 | 6.2202 | 5.79 | 13.3 |
| GSR | LO | 2/5 | 0.3936 | 5.79 | 13.3 |
| GSR | T** | 5/10 | 29.2897 | 3.33 | 5.64 |
| GSR | LT | 5/40 | 1.2654 | 2.45 | 3.51 |
| GSR | OT* | 10/40 | 2.2895 | 2.08 | 2.80 |
| S - D | R | 1/5 | 0.2556 | 6.61 | 16.3 |
| S - D | L** | 1/2 | 119.2659 | 18.5 | 98.5 |
| S - D | O | 2/5 | 0.6496 | 5.79 | 13.3 |
| S - D | LO | 2/5 | 0.2215 | 5.79 | 13.3 |
| S - D | T** | 5/10 | 65.1780 | 3.33 | 5.64 |
| S - D | LT** | 5/40 | 3.6863 | 2.45 | 3.51 |
| S - D | OT | 10/40 | 0.3111 | 2.08 | 2.80 |
| S | R | 1/5 | 0.2532 | 6.61 | 16.3 |
| S | L | 1/2 | 18.2765 | 18.5 | 98.5 |
| S | O | 2/5 | 1.9824 | 5.79 | 13.3 |
| S | LO | 2/5 | 0.8429 | 5.79 | 13.3 |
| S | T** | 5/10 | 21.3438 | 3.33 | 5.64 |
| S | LT** | 5/40 | 6.9848 | 2.45 | 3.51 |
| S | OT | 10/40 | 1.4608 | 2.08 | 2.80 |
| D | R | 1/5 | 5.2552 | 6.61 | 16.3 |
| D | L | 1/2 | 17.9226 | 18.5 | 98.5 |
| D | O* | 2/5 | 8.3491 | 5.79 | 13.3 |
| D | LO | 2/5 | 5.7826 | 5.79 | 13.3 |
| D | T** | 5/10 | 20.3728 | 3.33 | 5.64 |
| D | LT | 5/40 | 2.2149 | 2.45 | 3.51 |
| D | OT | 10/40 | 1.1032 | 2.08 | 2.80 |

* significant at the 5% level
** significant at the 1% level

at the slow speed. Tables 4 and 5 show, however, that speed had no significant effect on heart rate or on GSR. The author feels this is explained by the fact that either speed was sufficient to bring the subject to exhaustion over a short period of time. This unfortunate choice of speeds probably approached the upper threshold of subject capability.

The blood pressure differential did show high significant variation due to speed at the one per cent level for both experimental designs. These results appear to indicate a higher heart stroke-volume was attained even after the heart had reached its threshold rate.

Time Period.--The most significant result of this research was the effect of the six time periods within each task. The time effect was found to be significant at the one per cent level of confidence for all dependent variables in both experimental designs. It was decided to analyze the time effects by polynomial regression (28)(29). F ratios computed by this method of analysis are listed in Tables 6, 7, 8 and 9. After it had been determined which degree of a polynomial best characterized the effect of time on a given dependent variable, the regression equations were developed (Tables 10 and 11). The time effects were then plotted for a graphic presentation of their relation to the dependent variables (Figures 10 through 21). Actual data points on these graphs are represented by squares and triangles. The plotted curves represent the polynomial equations derived from the data. It is obvious these curves do not represent the actual, or expected, relationship between the variables. The faired-in curves superimposed on the graphs represent the apparent actual trend of the data. It will be

Table 6. Polynomial Regression Analysis; Experimental Design 265.

| Degree | HR | GSR | S - D | S | D |
|---|---|---|---|---|---|
| | Estimated F Values of T/OT | | | | |
| Linear | 261.6840** | 141.2236** | 115.8417** | 43.2922** | 125.8903** |
| Quadratic | 99.9221** | 0.4629 | 40.1660** | 28.1509** | 22.0285** |
| Cubic | 35.1097** | 0.2168 | 1.9617 | 4.8203* | 0.0020 |
| Quartic | 6.2704* | 0.0257 | 0.8747 | 2.1568 | 0.0072 |
| Quintic | 0.9827 | 0.1052 | 1.5609 | 2.0046 | 0.2678 |

*significant at the 5% level; $F_{.05;1,20} = 4.35$

**significant at the 1% level; $F_{.01;1,20} = 8.10$

Table 7. Polynomial Regression Analysis; Experimental Design 265.

| Degree | HR | GSR | S - D | S | D |
|---|---|---|---|---|---|
| | Estimated F Values of LT/SP Res | | | | |
| Linear | 60.0259** | 6.9202* | 35.9611** | 22.4899** | 11.8081** |
| Quadratic | 17.1099** | 0.2354 | 6.0463* | 7.3317* | 0.0353 |
| Cubic | 6.2110* | 0.7835 | 3.1301 | 5.1512* | 0.2378 |
| Quartic | 1.6090 | 0.7540 | 0.1411 | 0.1032 | 0.2710 |
| Quintic | 0.3040 | 0.0915 | 0.2532 | 0.0304 | 0.1204 |

*significant at the 5% level; $F_{.05;1,20} = 4.35$

**significant at the 1% level; $F_{.01;1,20} = 8.10$

Table 8. Polynomial Regression Analysis; Experimental Design 2623.

| Degree | HR | GSR | S - D | S | D |
|---|---|---|---|---|---|
| | Estimated F Values of T/OT | | | | |
| Linear | 341.3841** | 140.8284** | 203.5797** | 65.8758** | 83.2412** |
| Quadratic | 131.3623** | 4.8827 | 85.7336** | 31.8629** | 17.4301** |
| Cubic | 49.5888** | 0.0108 | 29.3475** | 4.3401 | 0.4947 |
| Quartic | 8.2217* | 0.4690 | 0.0164 | 3.9023 | 0.6899 |
| Quintic | 0.6848 | 0.2575 | 7.2130* | 0.7377 | 0.0080 |

*significant at the 5% level; $F_{.05;1,10} = 4.96$

**significant at the 1% level; $F_{.01;1,10} = 10.0$

Table 9. Polynomial Regression Analysis; Experimental Design 2623.

| Degree | HR | GSR | S - D | S | D |
|---|---|---|---|---|---|
| | Estimated F Values of LT/SP Res | | | | |
| Linear | 115.3689** | 3.6926 | 7.5246** | 20.3734** | 10.2731** |
| Quadratic | 11.0307** | 2.0217 | 2.3055 | 9.9005** | 0.0219 |
| Cubic | 3.8310 | 0.4355 | 5.6477* | 3.7821 | 0.0640 |
| Quartic | 0.1843 | 0.0042 | 1.3576 | 0.0587 | 0.5926 |
| Quintic | 0.2257 | 0.1730 | 1.5963 | 0.8094 | 0.1230 |

*significant at the 5% level; $F_{.05;1,40} = 4.08$

**significant at the 1% level; $F_{.01;1,40} = 7.31$

Table 10. Regression Equations for Significant Sources of Variation; Experimental Design 265.

| Source | Dependent Variable | Regression Equation |
|---|---|---|
| $L_1T$ | HR | $Y = 45.868 + 59.095t - 14.394t^2 + 1.130t^3$ |
| $L_2T$ | HR | $Y = 6.050 + 111.896t - 27.037t^2 + 2.127t^3$ |
| T | GSR | $Y = 25.928 + 0.903t$ |
| $L_1T$ | S - D | $Y = 31.075 + 16.709t - 1.929t^2$ |
| $L_2T$ | S - D | $Y = 21.122 + 37.643t - 3.807t^2$ |
| $L_1T$ | S B.P. | $Y = 111.735 + 7.724t - 0.954t^2$ |
| $L_2T$ | S B.P. | $Y = 101.678 + 24.992t - 2.700t^2$ |
| $L_1T$ | D B.P. | $Y = 80.660 - 8.985t + 0.975t^2$ |
| $L_2T$ | D B.P. | $Y = 80.556 - 12.651t + 1.107t^2$ |

Table 11. Regression Equations for Significant Sources of Variation; Experimental Design 2623.

| Source | Dependent Variable | Regression Equation |
|---|---|---|
| $O_2L_1T$ | HR | $Y = 66.824 + 46.517t - 11.580t^2 + 0.922t^3$ |
| $O_2L_2T$ | HR | $Y = 34.349 + 83.491t - 20.567t^2 + 1.643t^3$ |
| $O_3L_1T$ | HR | $Y = 24.169 + 74.467t - 18.702t^2 \quad 1.482t^3$ |
| $O_3L_2T$ | HR | $Y = 19.504 + 93.597t - 21.913t^2 + 1.708t^3$ |
| $O_4L_1T$ | HR | $Y = 25.672 + 73.811t - 18.254t^2 + 1.440t^3$ |
| $O_4L_2T$ | HR | $Y = 8.685 + 95.143t - 23.082t^2 + 1.828t^3$ |
| $T$ | GSR | $Y = 29.116 + 0.967t$ |
| $L_1T$ | S - D | $Y = 19.243 + 26.420t - 4.777t^2 + 0.267t^3$ |
| $L_2T$ | S - D | $Y = - 10.962 + 73.140t - 15.772t^2 + 1.128t^3$ |
| $L_1T$ | S B.P. | $Y = 104.567 + 10.169t - 1.095t^2$ |
| $L_2T$ | S B.P. | $Y = 91.962 + 27.458t - 3.030t^2$ |
| $L_1T$ | D B.P. | $Y = 79.316 - 7.998t + 0.882t^2$ |
| $L_2T$ | D B.P. | $Y = 74.800 - 10.126t + 0.911t^2$ |

noted in some cases that the computed and actual curves were thought to coincide. Only GSR was found to be linearly affected by time. Correlations computed for this linear effect were 0.8305 in experimental design 265 and 0.8167 in experimental design 2623. It will be noted in Figures 10 through 21 that GSR is the only variable for which the time effect was summed over both speeds. For the other dependent variables the load-time interaction was considered significant enough to justify a distinct curve for each speed. In the case of heart rate the operator-time interaction was significant enough in experiment 2623 to require an additional set of curves (Figures 11, 12 and 13) for each subject.

Interactions.--The load-operator interaction produced no significant variation in any of the dependent variables. This would appear to indicate no need for a stratification of workers by fitness; however, in view of the absence of a discriminating load effect it is probably true that the loads were severe enough to bring all the subjects to the threshold rate of energy expenditure regardless of their relative condition.

The operator-time interaction produced a significant variation in heart rate and GSR for experiment 2623. Since this was considered to be a relatively homogeneous group of subjects, heart rate, significant at the one per cent level, appears to distinguish between operators for small groups of subjects. Lack of operator-time interaction significance in experiment 265 indicates all the dependent variables may be good measures of high energy expenditure even in the case of heterogeneous groups if the subject sample is large enough.

As was expected, the speed-time interaction was highly significant for heart rate, blood pressure differential and systolic blood pressure for both experimental designs. The speed-time interaction is, in effect, a measure of the work accomplished at any given time and is composed of the two main factors involved in physiological fatigue. While the load alone had no significant effect on heart rate, its interaction with time was sufficient to differentiate between the effects of the two loads within the limitations of this experiment. This is clearly seen in Figures 10 through 21. It should be noted that time and the speed-time interaction were split-plot variables which could reach significance easier than the main plot speed variable due to their smaller residual variance.

Concomitants.--Although concomitants were not subjected to a formal analysis, the evidence of their effect is indicated in Tables 12 and 13. A comparison of the error variances between main plot and split plot variables shows a large day to day variation for heart rate and galvanic skin response. The smaller ratios of main plot error variance to split plot error variance for the blood pressure variables indicate the value of these variables as measures free from the daily variation in concomitants.

Table 12. Error Mean Squares and Standard Deviations for Dependent Variables; Experimental Design 265.

| | Main Plot | | Split Plot | |
|---|---|---|---|---|
| | Variance | Std. Dev. | Variance | Std. Dev. |
| HR | 1483.400 | 38.515 | 25.890 | 5.088 |
| GSR | 100949.042 | 317.725 | 4132.152 | 64.282 |
| S - D | 176.208 | 13.275 | 71.118 | 8.433 |
| S | 197.004 | 14.035 | 42.399 | 6.512 |
| D | 103.267 | 10.162 | 30.367 | 5.511 |

Table 13. Error Mean Squares and Standard Deviations for Dependent Variables; Experimental Design 2623.

| | Main Plot | | Split Plot | |
|---|---|---|---|---|
| | Variance | Std. Dev. | Variance | Std. Dev. |
| HR | 336.314 | 18.339 | 10.093 | 3.177 |
| GSR | 53876.581 | 232.113 | 2300.066 | 47.959 |
| S - D | 500.767 | 22.378 | 131.591 | 11.471 |
| S | 396.281 | 19.907 | 39.771 | 6.307 |
| D | 22.858 | 4.781 | 18.081 | 4.252 |

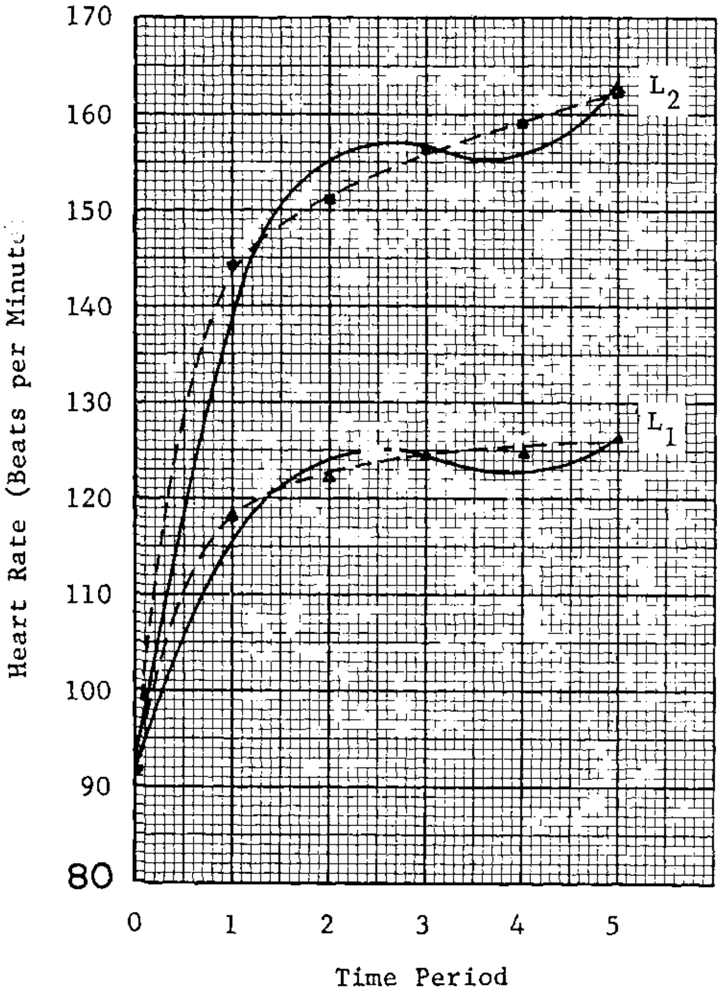


Figure 10. The Effect of Load-Time Interaction on Heart Rate; Experimental Design 265.

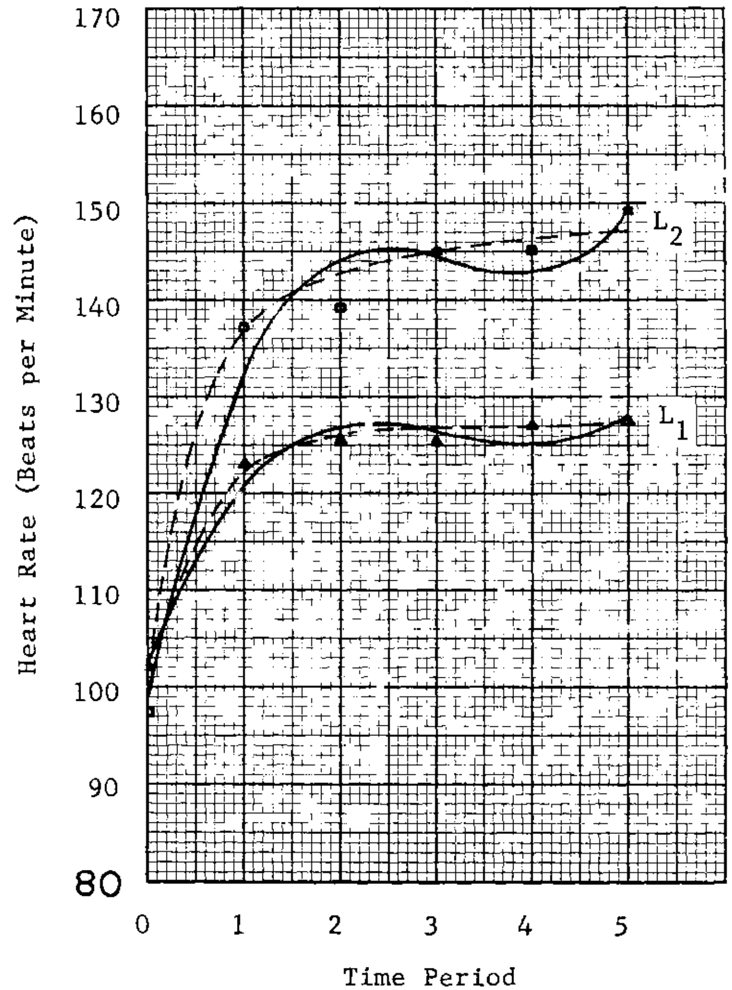


Figure 11. The Effect of Load-Time Interaction on Heart Rate, Operator No. 2; Experimental Design 2623.

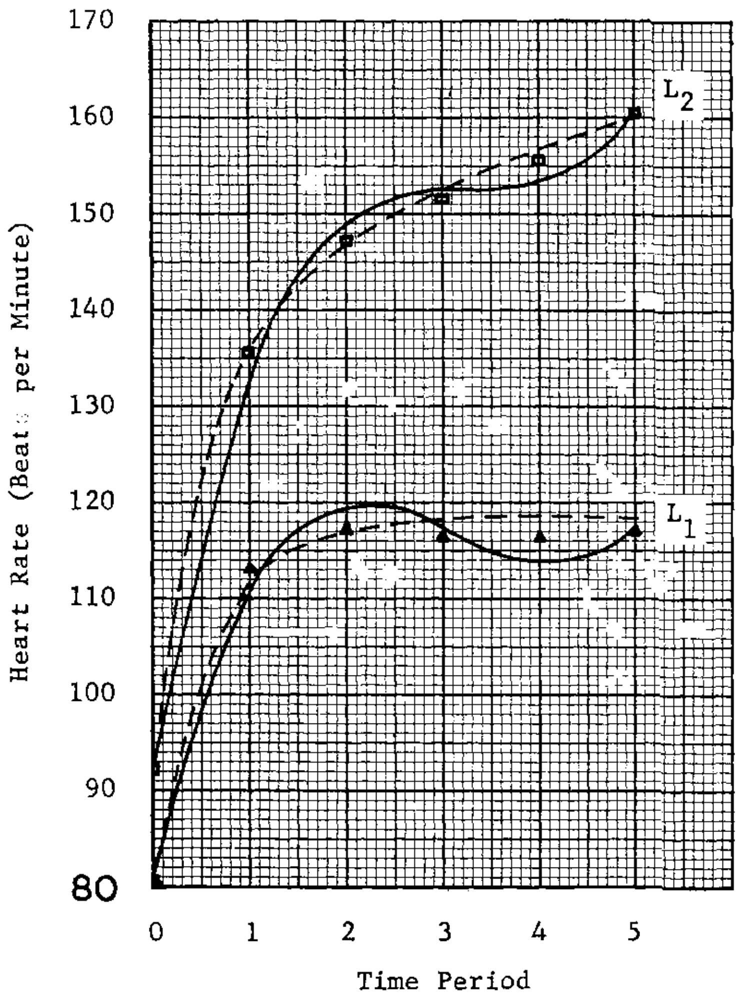


Figure 12. The Effect of Load-Time Interaction on Heart Rate, Operator No. 3; Experimental Design 2623.

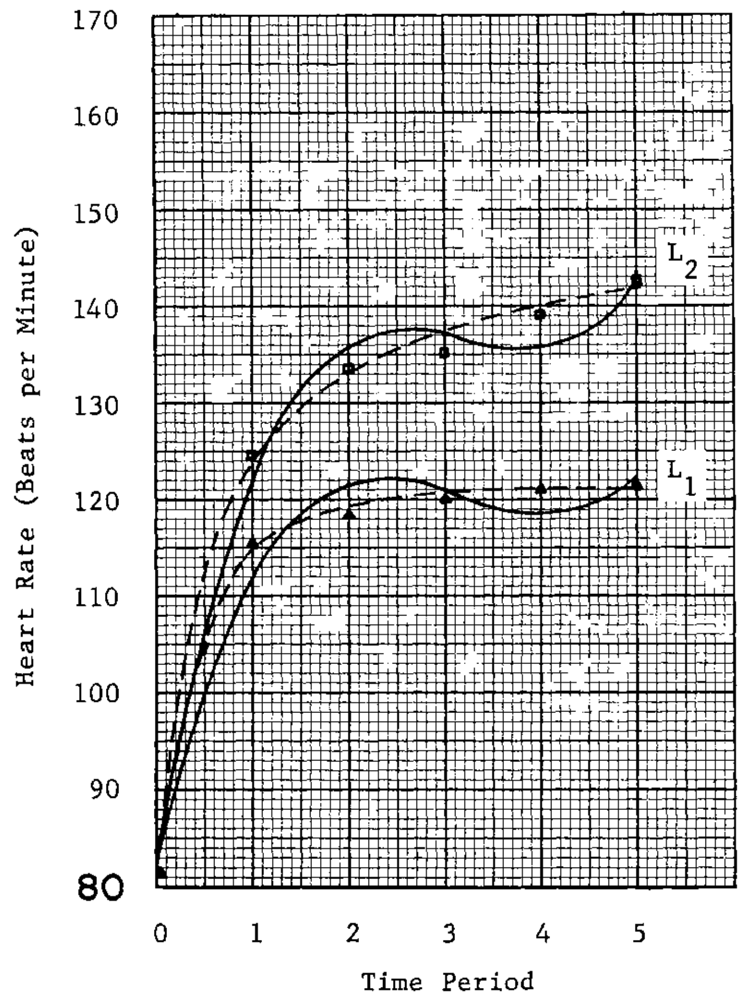


Figure 13. The Effect of Load-Time Interaction on Heart Rate, Operator No. 4; Experimental Design 2623.

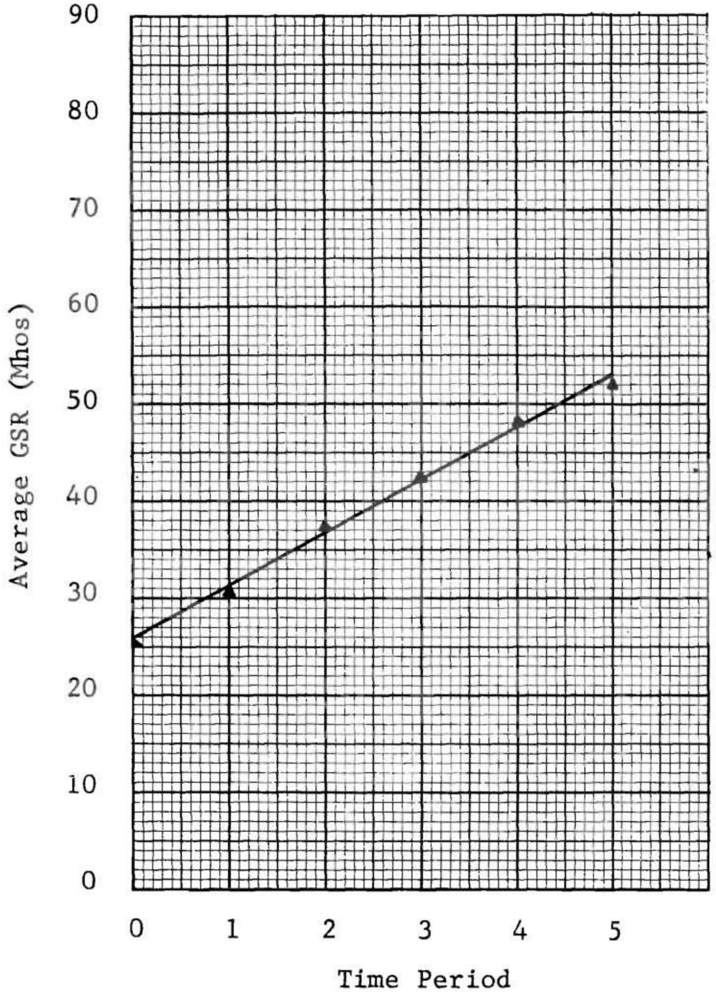


Figure 14. The Effect of Time on Galvanic Skin Response; Experimental Design 265.

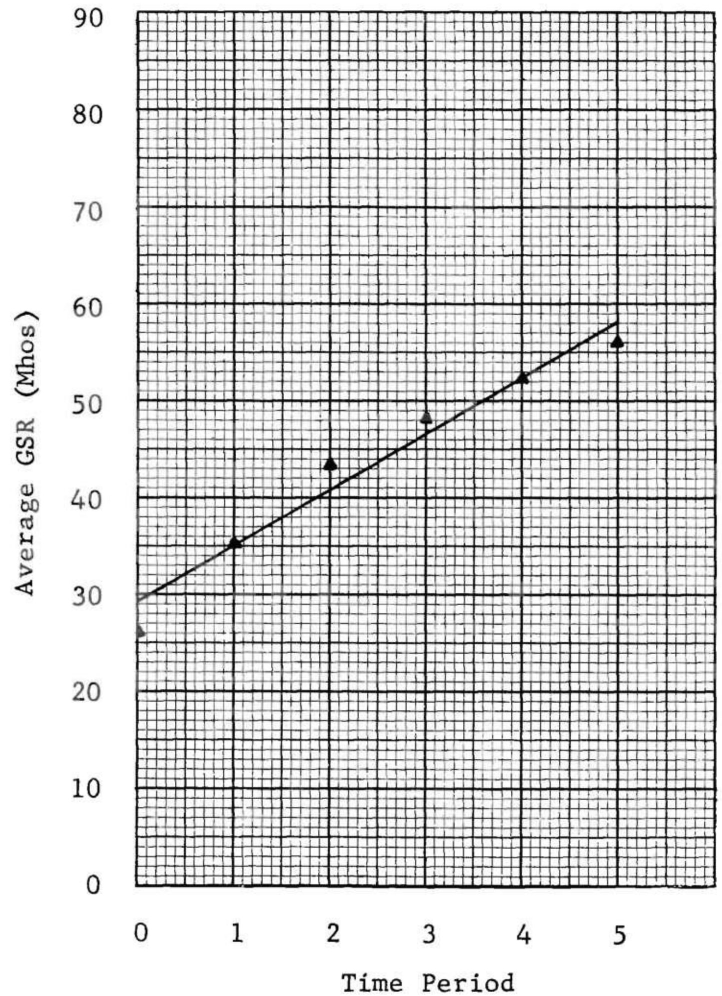


Figure 15. The Effect of Time on Galvanic Skin Response; Experimental Design 2623.

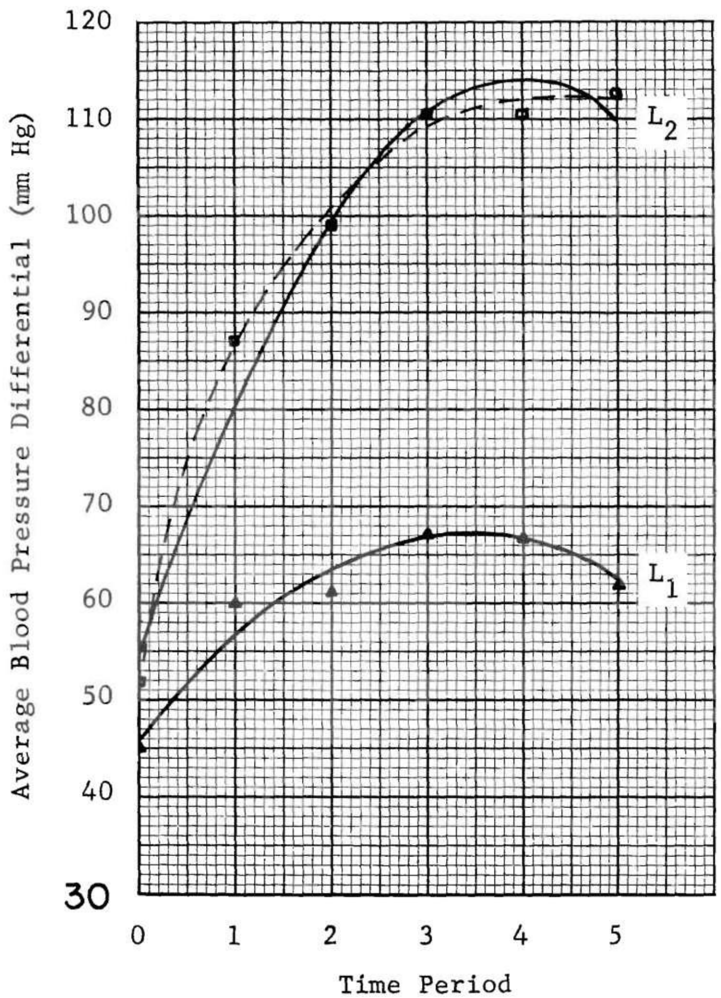


Figure 16. The Effect of Load-Time Interaction on Systolic-Diastolic Blood Pressure Differential; Experimental Design 265.

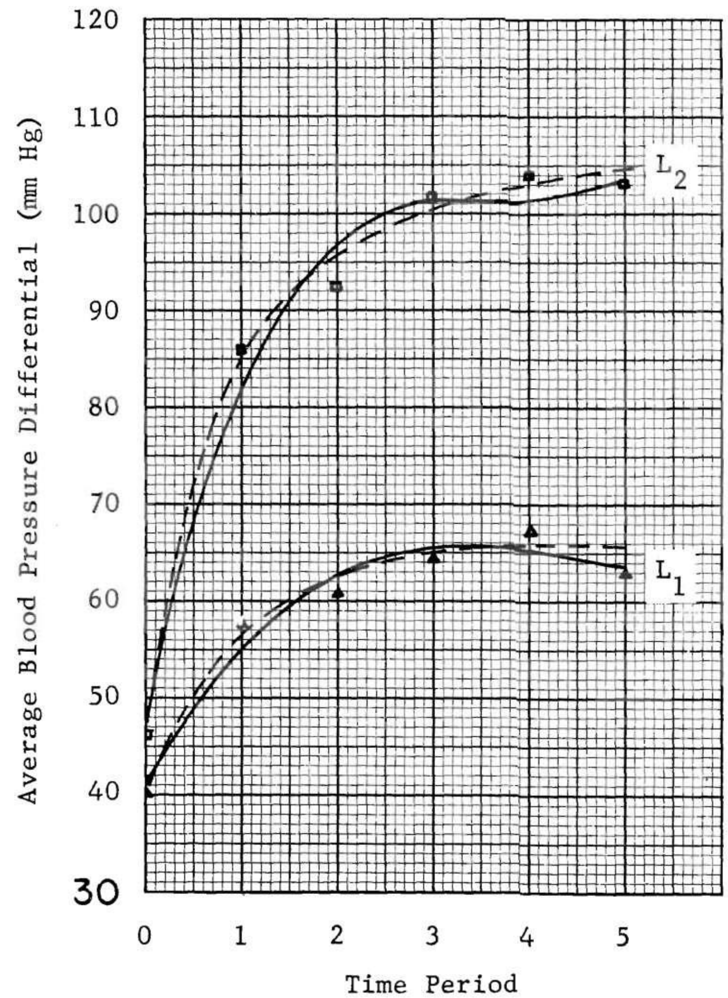


Figure 17. The Effect of Load-Time Interaction on Systolic-Diastolic Blood Pressure Differential; Experimental Design 2623.

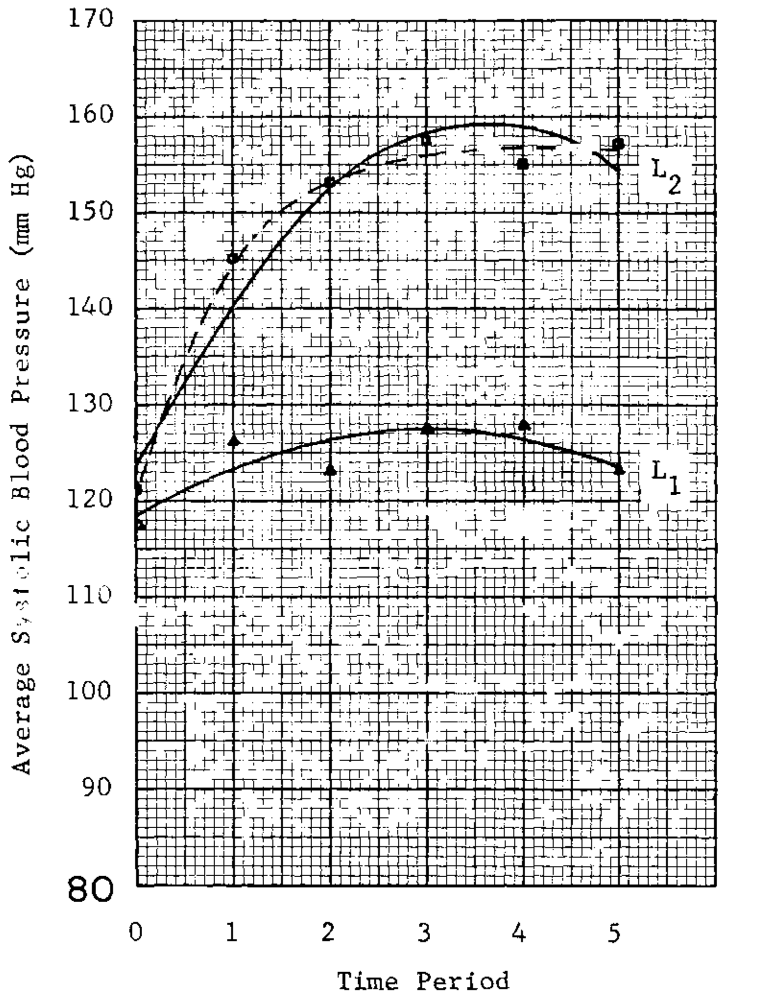


Figure 18. The Effect of Load-Time Interaction on Systolic Blood Pressure; Experimental Design 265.

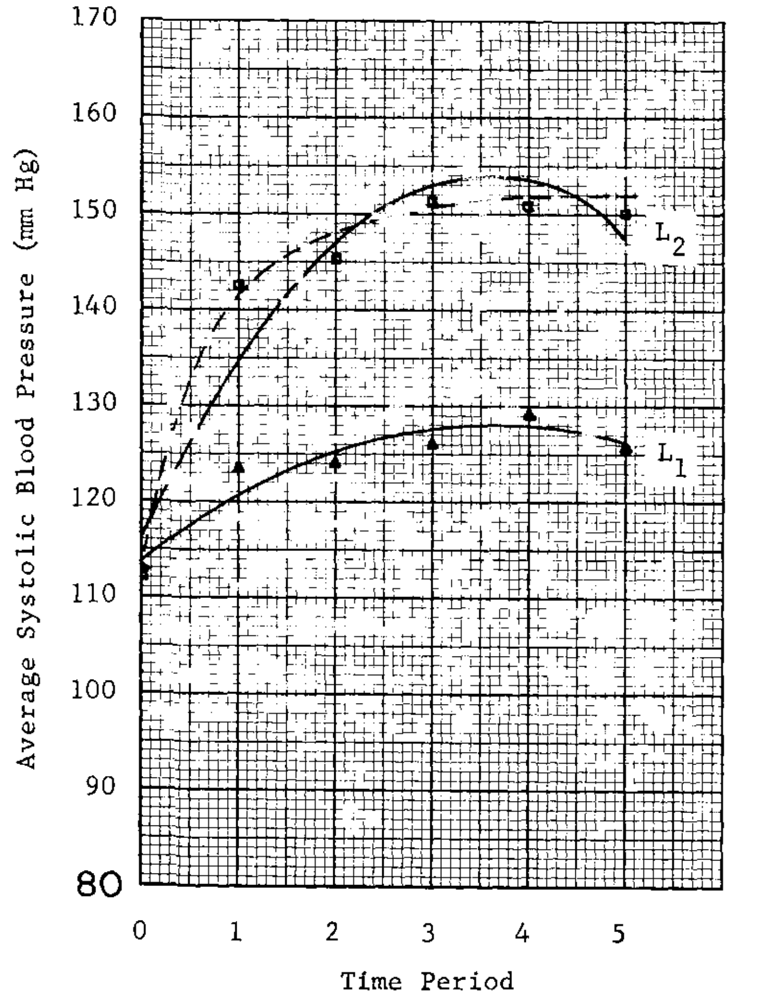


Figure 19. The Effect of Load-Time Interaction on Systolic Blood Pressure; Experimental Design 2623.

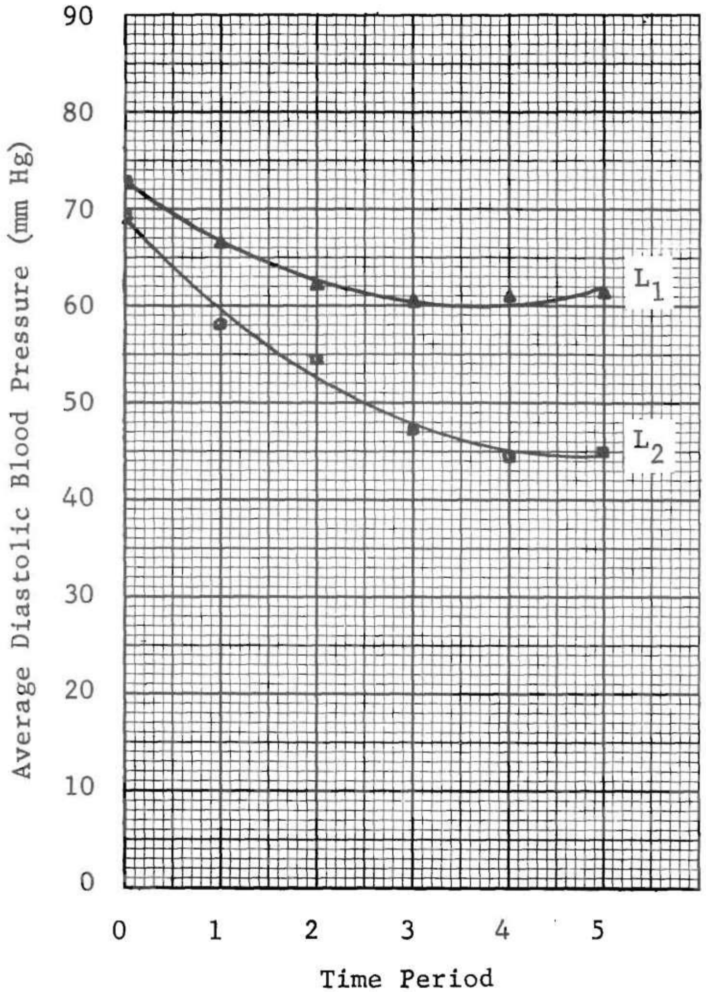


Figure 20. The Effect of Load-Time Interaction on Diastolic Blood Pressure; Experimental Design 265.

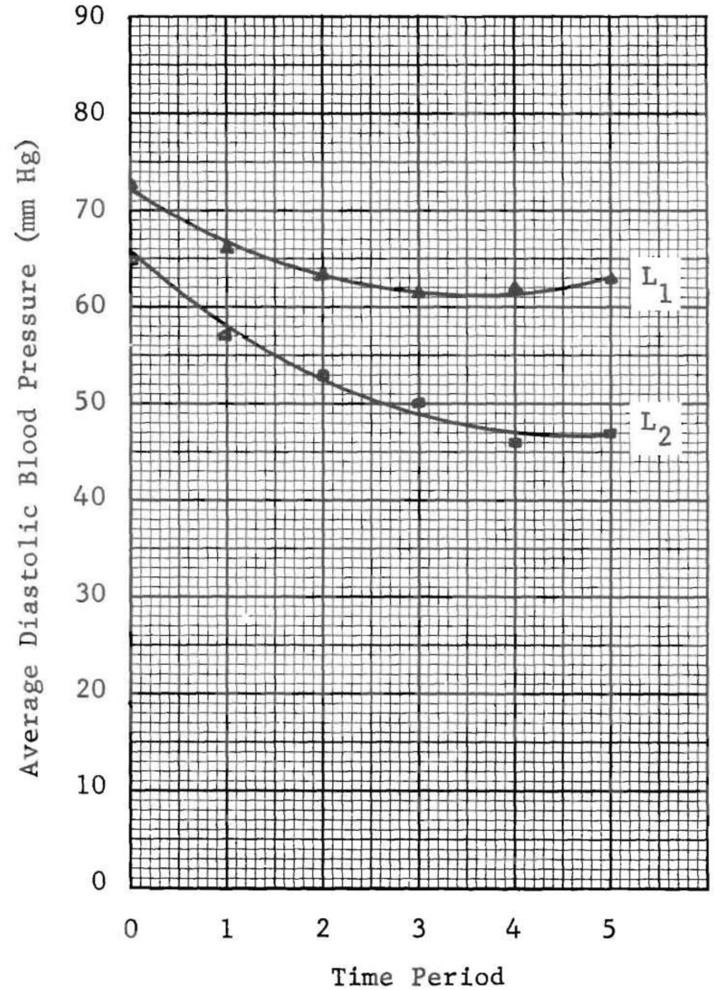


Figure 21. The Effect of Load-Time Interaction on Diastolic Blood Pressure; Experimental Design 2623.

# CHAPTER VI

## CONCLUSIONS AND RECOMMENDATIONS

Results of this research indicate that in exhaustive tasks, involving heavy physical work for short periods of time, the time the load is attended is the most significant contributor to fatigue beyond the effect of the load itself. Under the conditions of this experiment, heart rate, galvanic skin response and blood pressure differential were all seen to increase significantly as time at the task progressed. In industrial jobs requiring severe physical exertion these variables can probably be proven accurate indicators of fatigue. Further research to validate results of this experiment should be conducted over longer periods of time and under lighter load conditions which will permit clarification of the effects of the different contributing factors of fatigue.

One of the most encouraging, but least expected, results of this research was the relation between subjects and blood pressure differential. Only slight significant variation was found among subjects for the difference between systolic and diastolic blood pressures. In previous research (30) it was suspected that this lack of significance could be attributed to low energy output; however, it is now seen that such is not the case. This variable is apparently worthy of further study and should be investigated under more moderate load conditions for longer periods of time. Another interesting observation regarding blood pressure differential was its discrimination among loads as the heart rate approached a maximum. This could be important as a more definitive measure in classifying jobs already thought to be exhaustive.

The author would like to point out that the variables investigated in this research are not operational at this time. The complexity and sensitivity of the equipment used renders the recording process too cumbersome for on-the-job investigation. Familiarity with the heart rate trace and its possible artifacts is essential to its analysis. It is felt that further research in this area will lead to recording techniques, not necessarily as sensitive as those used in this experiment, which will be both definitive and operational.

Results of this research can hardly be considered as indicative of cardiac behavior, or of reactions of the body as a whole, over the span of a working day. Long term studies are recommended for their possible insight into the effects of cumulative fatigue. It is also considered essential that studies be made of the relation between rest periods and cumulative fatigue.

It should be noted that this experiment concentrated stress upon a particular muscle grouping. This leaves open to investigation the effects of exertion involving the entire body. Such factors as posture, extreme variation in fitness and age, etc., must all be considered in order to define the entire spectrum of reasonable variation in human energy expenditure.

# APPENDICES

## APPENDIX A-I

### CODED DATA, HEART RATE

| | Replication 1 | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Speed 1 | | | | | | Speed 2 | | | | | |
| | $t_0$ | $t_1$ | $t_2$ | $t_3$ | $t_4$ | $t_5$ | $t_0$ | $t_1$ | $t_2$ | $t_3$ | $t_4$ | $t_5$ |
| $0_1$ | 0 | 32 | 32 | 37 | 37 | 40 | 20 | 92 | 97 | 106 | 105 | 111 |
| $0_2$ | 37 | 51 | 56 | 56 | 57 | 57 | 18 | 62 | 64 | 67 | 67 | 69 |
| $0_3$ | 2 | 31 | 32 | 32 | 31 | 31 | 21 | 57 | 69 | 74 | 81 | 88 |
| $0_4$ | 5 | 40 | 43 | 45 | 46 | 46 | 13 | 56 | 62 | 65 | 71 | 71 |
| $0_5$ | 37 | 62 | 73 | 75 | 77 | 81 | 10 | 78 | 88 | 94 | 95 | 97 |

| | Replication 2 | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Speed 1 | | | | | | Speed 2 | | | | | |
| | $t_0$ | $t_1$ | $t_2$ | $t_3$ | $t_4$ | $t_5$ | $t_0$ | $t_1$ | $t_2$ | $t_3$ | $t_4$ | $t_5$ |
| $0_1$ | 5 | 45 | 52 | 45 | 48 | 50 | 10 | 93 | 110 | xx | xx | xx |
| $0_2$ | 17 | 45 | 45 | 45 | 47 | 48 | 27 | 62 | 64 | 73 | 73 | 79 |
| $0_3$ | 9 | 45 | 52 | 51 | 52 | 53 | 13 | 64 | 75 | 79 | 80 | 83 |
| $0_4$ | 8 | 41 | 44 | 45 | 46 | 47 | 0 | 43 | 55 | 55 | 57 | 64 |
| $0_5$ | 5 | 43 | 45 | 55 | 55 | 56 | 6 | 71 | 112 | xx | xx | xx |

APPENDIX A-II

CODED DATA, GSR

| | Replication 1 | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Speed 1 | | | | | | Speed 2 | | | | | |
| | $t_0$ | $t_1$ | $t_2$ | $t_3$ | $t_4$ | $t_5$ | $t_0$ | $t_1$ | $t_2$ | $t_3$ | $t_4$ | $t_5$ |
| $O_1$ | 165 | 187 | 201 | 221 | 261 | 301 | 291 | 461 | 601 | 701 | 831 | 881 |
| $O_2$ | 202 | 166 | 296 | 331 | 341 | 356 | 0 | 146 | 179 | 226 | 281 | 326 |
| $O_3$ | 301 | 351 | 451 | 511 | 561 | 601 | 361 | 341 | 557 | 633 | 715 | 761 |
| $O_4$ | 191 | 161 | 261 | 296 | 349 | 351 | 231 | 281 | 321 | 361 | 401 | 461 |
| $O_5$ | 106 | 96 | 151 | 211 | 251 | 286 | 121 | 96 | 146 | 191 | 241 | 286 |

| | Replication 2 | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Speed 1 | | | | | | Speed 2 | | | | | |
| | $t_0$ | $t_1$ | $t_2$ | $t_3$ | $t_4$ | $t_5$ | $t_0$ | $t_1$ | $t_2$ | $t_3$ | $t_4$ | $t_5$ |
| $O_1$ | 251 | 241 | 291 | 391 | 411 | 541 | 501 | 549 | 741 | xx | xx | xx |
| $O_2$ | 136 | 151 | 176 | 226 | 241 | 216 | 146 | 331 | 481 | 531 | 551 | 541 |
| $O_3$ | 256 | 411 | 541 | 611 | 711 | 801 | 231 | 361 | 441 | 501 | 541 | 561 |
| $O_4$ | 151 | 261 | 331 | 316 | 386 | 441 | 251 | 371 | 481 | 541 | 501 | 571 |
| $O_5$ | 91 | 104 | 151 | 196 | 241 | 291 | 91 | 91 | 166 | xx | xx | xx |

# APPENDIX A-III

## CODED DATA, B.P. DIFF.

| | Replication 1 | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Speed 1 | | | | | | Speed 2 | | | | | |
| | $t_0$ | $t_1$ | $t_2$ | $t_3$ | $t_4$ | $t_5$ | $t_0$ | $t_1$ | $t_2$ | $t_3$ | $t_4$ | $t_5$ |
| $O_1$ | 48 | 58 | 68 | 72 | 74 | 72 | 38 | 56 | 94 | 114 | 118 | 108 |
| $O_2$ | 16 | 30 | 38 | 38 | 46 | 34 | 30 | 70 | 64 | 92 | 90 | 92 |
| $O_3$ | 26 | 48 | 40 | 53 | 42 | 28 | 22 | 68 | 80 | 84 | 86 | 98 |
| $O_4$ | 16 | 20 | 22 | 26 | 34 | 34 | 33 | 73 | 72 | 72 | 72 | 74 |
| $O_5$ | 18 | 23 | 28 | 38 | 28 | 31 | 26 | 58 | 74 | 80 | 76 | 80 |

| | Replication 2 | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Speed 1 | | | | | | Speed 2 | | | | | |
| | $t_0$ | $t_1$ | $t_2$ | $t_3$ | $t_4$ | $t_5$ | $t_0$ | $t_1$ | $t_2$ | $t_3$ | $t_4$ | $t_5$ |
| $O_1$ | 40 | 86 | 82 | 66 | 78 | 82 | 42 | 112 | 131 | xx | xx | xx |
| $O_2$ | 16 | 50 | 60 | 48 | 62 | 50 | 24 | 56 | 68 | 86 | 112 | 92 |
| $O_3$ | 20 | 40 | 40 | 44 | 48 | 48 | 20 | 56 | 70 | 72 | 60 | 66 |
| $O_4$ | 16 | 26 | 32 | 46 | 40 | 50 | 16 | 60 | 68 | 72 | 70 | 64 |
| $O_5$ | 13 | 54 | 60 | 68 | 70 | 70 | 26 | 68 | 70 | xx | xx | xx |

# APPENDIX A-IV

## CODED DATA, SYSTOLIC B.P.

| | Replication 1 | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Speed 1 | | | | | | Speed 2 | | | | | |
| | $t_0$ | $t_1$ | $t_2$ | $t_3$ | $t_4$ | $t_5$ | $t_0$ | $t_1$ | $t_2$ | $t_3$ | $t_4$ | $t_5$ |
| $O_1$ | 62 | 78 | 82 | 84 | 88 | 84 | 70 | 82 | 110 | 110 | 110 | 106 |
| $O_2$ | 44 | 52 | 56 | 56 | 62 | 50 | 54 | 82 | 76 | 98 | 90 | 90 |
| $O_3$ | 64 | 74 | 64 | 74 | 64 | 54 | 46 | 86 | 94 | 88 | 88 | 98 |
| $O_4$ | 44 | 44 | 40 | 40 | 46 | 46 | 54 | 84 | 82 | 88 | 86 | 88 |
| $O_5$ | 44 | 54 | 44 | 54 | 49 | 52 | 52 | 62 | 74 | 74 | 70 | 74 |

| | Replication 2 | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Speed 1 | | | | | | Speed 2 | | | | | |
| | $t_0$ | $t_1$ | $t_2$ | $t_3$ | $t_4$ | $t_5$ | $t_0$ | $t_1$ | $t_2$ | $t_3$ | $t_4$ | $t_5$ |
| $O_1$ | 62 | 92 | 92 | 80 | 86 | 98 | 62 | 116 | 122 | xx | xx | xx |
| $O_2$ | 40 | 68 | 76 | 66 | 82 | 68 | 40 | 72 | 76 | 86 | 98 | 82 |
| $O_3$ | 50 | 66 | 66 | 66 | 70 | 72 | 42 | 70 | 76 | 76 | 74 | 76 |
| $O_4$ | 40 | 42 | 46 | 58 | 56 | 66 | 42 | 66 | 71 | 74 | 72 | 70 |
| $O_5$ | 44 | 72 | 72 | 74 | 74 | 74 | 62 | 84 | 80 | xx | xx | xx |

# APPENDIX A-V

## CODED DATA, DIASTOLIC B.P.

| | Replication 1 | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Speed 1 | | | | | | Speed 2 | | | | | |
| | $t_0$ | $t_1$ | $t_2$ | $t_3$ | $t_4$ | $t_5$ | $t_0$ | $t_1$ | $t_2$ | $t_3$ | $t_4$ | $t_5$ |
| $O_1$ | 38 | 34 | 28 | 26 | 28 | 26 | 46 | 40 | 30 | 10 | 6 | 12 |
| $O_2$ | 42 | 36 | 32 | 32 | 30 | 30 | 38 | 26 | 26 | 20 | 14 | 12 |
| $O_3$ | 52 | 40 | 38 | 35 | 36 | 40 | 38 | 32 | 28 | 18 | 16 | 14 |
| $O_4$ | 42 | 38 | 32 | 28 | 26 | 26 | 35 | 25 | 24 | 30 | 28 | 28 |
| $O_5$ | 40 | 35 | 30 | 30 | 35 | 35 | 40 | 18 | 14 | 8 | 8 | 8 |

| | Replication 2 | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Speed 1 | | | | | | Speed 2 | | | | | |
| | $t_0$ | $t_1$ | $t_2$ | $t_3$ | $t_4$ | $t_5$ | $t_0$ | $t_1$ | $t_2$ | $t_3$ | $t_4$ | $t_5$ |
| $O_1$ | 36 | 20 | 24 | 28 | 32 | 30 | 34 | 18 | 5 | xx | xx | xx |
| $O_2$ | 38 | 32 | 30 | 32 | 34 | 32 | 30 | 30 | 22 | 18 | 0 | 4 |
| $O_3$ | 44 | 40 | 40 | 36 | 36 | 38 | 36 | 28 | 20 | 18 | 22 | 24 |
| $O_4$ | 38 | 30 | 28 | 26 | 30 | 30 | 40 | 20 | 18 | 16 | 16 | 20 |
| $O_5$ | 45 | 32 | 26 | 20 | 18 | 18 | 50 | 30 | 24 | xx | xx | xx |

# APPENDIX B-I

## ANALYSIS OF VARIANCE COMPONENTS FOR SUMS OF SQUARES

Experimental Design 265

| | $T^2_{...}/60$ | | $\sum_i T^2_{i..}/30$ | | $\sum_j T^2_{.j.}/10$ |
|---|---|---|---|---|---|
| HR | 186930.0166 | HR | 197252.8333 | HR | 206691.7000 |
| GSR | 6752273.0666 | GSR | 6912439.7333 | GSR | 7271274.6000 |
| S-D | 187936.0666 | S-D | 206662.7333 | S-D | 199520.8000 |
| S | 299202.8166 | S | 308304.8333 | S | 302916.9000 |
| D | 49249.3500 | D | 50966.7000 | D | 51906.5000 |

| | $\sum_k T^2_{..k}/12$ | | $\sum_{ij} T^2_{ij.}/5$ | | $\sum_{ik} T^2_{i.k}/6$ |
|---|---|---|---|---|---|
| HR | 192471.7499 | HR | 219221.8000 | HR | 208728.1666 |
| GSR | 7578046.1666 | GSR | 7467740.4000 | GSR | 8142008.9999 |
| S-D | 195212.8333 | S-D | 221485.6000 | S-D | 214644.3333 |
| S | 305656.7999 | S | 313507.4000 | S | 315546.8333 |
| D | 49574.7499 | D | 54002.6000 | D | 51705.1666 |

| | $\sum_{jk} T^2_{.jk}/2$ | | $\sum_{ijk} T^2_{ijk}$ |
|---|---|---|---|
| HR | 213211.5000 | HR | 232192.0000 |
| GSR | 8170129.0000 | GSR | 8853034.0000 |
| S-D | 208242.0000 | S-D | 232334.0000 |
| S | 310294.5000 | S | 322521.0000 |
| D | 52590.5000 | D | 55707.0000 |

# APPENDIX B-II

## ANALYSIS OF VARIANCE COMPONENTS FOR SUMS OF SQUARES

Experimental Design 2623

| | $T^2{}_{....}/72$ | | $\sum_i T^2{}_{i...}/36$ | | $\sum_j T^2{}_{.j..}/12$ |
|---|---|---|---|---|---|
| HR | 175923.3472 | HR | 182402.3611 | HR | 194763.2499 |
| GSR | 10091278.1250 | GSR | 10151078.1250 | GSR | 10862482.9166 |
| S-D | 183012.5000 | S-D | 196242.7222 | S-D | 196354.9999 |
| S | 320934.0138 | S | 327039.1388 | S | 327134.0833 |
| D | 60146.6805 | D | 62515.6944 | D | 62178.5833 |

| | $\sum_k T^2{}_{..k.}/36$ | | $\sum_l T^2{}_{...l}/24$ | | $\sum_{ij} T^2{}_{ij..}/6$ |
|---|---|---|---|---|---|
| HR | 175925.6944 | HR | 176935.2083 | HR | 202560.8333 |
| GSR | 10128497.1388 | GSR | 10761522.4583 | GSR | 10936835.8333 |
| S-D | 183140.5000 | S-D | 183663.0833 | S-D | 212010.6666 |
| S | 321034.3611 | S | 322505.2083 | S | 334628.1666 |
| D | 60266.8055 | D | 60528.3749 | D | 64747.8333 |

| | $\sum_{jl} T^2{}_{.j.l}/4$ | | $\sum_{ikl} T^2{}_{i.kl}/6$ | | $\sum_{ijkl} y^2{}_{ijkl}$ |
|---|---|---|---|---|---|
| HR | 196129.7500 | HR | 186244.1666 | HR | 207161.0000 |
| GSR | 11585387.7500 | GSR | 11170338.4999 | GSR | 12100759.0000 |
| S-D | 197415.0000 | S-D | 199746.9999 | S-D | 221188.0000 |
| S | 329286.2500 | S | 331360.1666 | S | 341121.0000 |
| D | 62759.7500 | D | 63396.1666 | D | 66551.0000 |

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